Atmospheric Water Vapor Calibrations: Radiometer Technique

F. B. Winn, S. C. Wu, G. M. Resch,
C. C. Chao, and O. H. von Roos
Tracking and Orbit Determination Section

H. S. Lau
Stanford University

A radiometric technique for determining atmospheric water vapor effects on radiometric range and doppler has been partially evaluated. Empirical test results indicate that the microwave thermal emission from water vapor at 22.2 and 31.4 GHz frequencies can yield line-of-sight electrical phase path calibrations to the centimeter accuracy level.

I. Introduction

A radiometric technique for determining atmospheric water vapor effects on radiometric range and doppler has been partially evaluated. Empirical test results indicate that the microwave thermal emission from water vapor at 22.2 and 31.4 GHz frequencies can yield line-of-sight electrical phase path calibrations to the centimeter accuracy level. For range observations acquired at low elevation angles ($<$ 10 deg), this represents a 10-fold improvement over alternative calibration techniques.

Atmospheric water vapor imposes a small but important change in the electrical phase path length of signals that propagate through the atmosphere that is of importance to Earth-based ranging systems.

Each space mission/project specifies to the DSN its requirements for atmospheric refraction calibration. Viking 1975 (VK'75) states that the accumulated doppler error (relative range change) over an entire tracking pass (from 6 deg to 6 deg topocentric elevation) is not to exceed 1 meter (1 σ). Mariner Jupiter/Saturn 1977 (MJS'77) requires the integrated doppler error over a pass (from 10 deg to 10 deg topocentric elevation) not to exceed 0.5 m (1 σ).

Because of atmospheric refraction, the apparent range of a spacecraft as measured by the Deep Space Network is equal to the geometric range (from the Deep Space Station to the spacecraft) plus $\int_L n(\ell)\, d\ell$, where n is the atmospheric refractive index with the integration extending over the entire ray path.

The range error may be written as $10^{-6} \int_L N \, d\ell$ where N, the refractivity, equals $(n-1)\, 10^6$.

The refractivity due to the dry, predictable component can be separated from the wet component. The wet component, $10^{-6} \int_L N_\omega(\ell)\, d\ell$, is not predictable. It must be measured.

II. "Waterline" Radiometer: Thermal Emission Measurements

A near-linear relationship exists between $\int_L N_\omega(\ell)\, d\ell$ and $\int_L \alpha_\omega(\ell)\, d\ell$ *where* $\alpha_\omega(\ell)$ is the water vapor absorption coefficient for microwave frequencies near 22.2 GHz (the waterline). This relationship holds for the normal atmospheric temperature, pressure, and water vapor concentration levels encountered over DSN Deep Space Stations.

The Scanning Microwave Inversion Layer Experiment (SMILE) radiometer (Ref. 1) receives radiation at $\sim$ 22.2 GHz (waterline) and at $\sim$ 31.4 GHz. The measured thermal emission at both frequencies is proportional to the collective amounts of liquid and vapor water within the antenna beam. The brightness temperature at either frequency can be expressed via the radiative transfer equation

$$T_\nu = \int_L T(\ell)\, \alpha(\ell,\nu)\, e^{-\tau(\ell)}\, d\ell$$

where

$T(\ell)$ = temperature at ℓ

$\alpha(\ell,\nu)$ = absorption coefficient at ℓ for frequency ν

$\tau(\ell)$ = optical depth at ℓ

By approximating the atmosphere as isothermal and of small optical depth ($\tau << 1$), Waters (Ref. 2) has shown

$$T_\nu \approx \int_L \alpha(\ell,\nu)\, d\ell$$

which in turn is proportional to the electrical phase path delay $\Delta\rho$ experienced by a radio metric data type.

The thermal emission measured at either frequency is proportional to water in both liquid and vapor states. Electrical phase path delay due to liquid water is orders of magnitude less than the vapor-induced delay. Thus, only the collective amount of water vapor is of interest. To separate the liquid from the vapor, Longbothum[1] matched radiosonde-balloon-data water-vapor assessments to sky temperature brightness measurements via regression analysis:

$$\Delta\rho = a_0 + a_1 T_{22.2} + a_2 T_{31.4}$$

where a_0, a_1 and a_2 are regression coefficients resulting from a least squares fit of the sky temperature measurements at the 22.2 and 31.4 GHz frequencies to the radiosonde phase path delay computations. With a_0, a_1 and a_2 estimated, any set of T_{22} and T_{31} measurements yields an estimated $\Delta\rho$.

In the next portion of this article are empirical test results which discuss comparisons of "waterline" radiometer calibrations with calibrations derived from radiosonde, aircraft instrumentation, and models.

III. Radiometer-Radiosonde Comparison: May 1974

In May 1974, at El Monte, California, Waters showed that such phase delay determinations from SMILE are consistent with radiosonde delay determinations over times of weeks, once the two measurement sets have been matched. The rms discrepancy between the two calibrations for the time period (Fig. 1) is 1.62 cm. The shaded area indicates the radiosonde calibrations and their associated 2-cm (one standard deviation) uncertainty.

A radiosonde, a small electronic instrument, is suspended beneath a weather balloon. As the balloon ascends to 3 km (10,000 ft) or higher, it radios to ground receivers measurements of

absolute pressure p, σ_P = 2 mb

ambient temperature T, σ_T = 1°C

relative humidity RH, σ_{RH} = 5–10% for $RH > 20\%$

= 10–90% for $RH < 20\%$

to the accuracies indicated.

The zenith electrical phase path delay due to water vapor is

$$\Delta\rho = 10^6 \int_0^\infty N_\omega\, dh = k \int_0^\infty \frac{e_v}{(T+273)^2}$$

[1]Private communication (JPL).

from which

$$\Delta\rho = 6.11\,k \sum_i (RH)_i \, 10^{aT_i/(T_i+b)} \frac{\Delta h_i}{(T_i+273)^2} \qquad (1)$$

where $\Delta h_i \equiv i$th altitude increment in meters, T is in °C and $\Delta\rho$ is in cm.

$a = 7.5$, $b = 237.3$, $k = 0.373256$ (empirical constants, Ref. 3).

For zenith paths, water vapor calibrations to the 90% accuracy level ($\sigma = 2$ cm) are achieved.

IV. Radiometer-Aircraft Comparisons: November 1974

In November 1974, over the JPL complex at Pasadena, California, an aircraft owned and operated by Meteorological Research, Inc. (MRI) flew from 900 m to 6 km (3000 to 20,000 ft) in 50 minutes. Pressure, temperature and dewpoint temperature were measured as functions of altitude and time. The aircraft instrumentation measures

absolute pressure P, $\sigma_P = 1$ mb

ambient temperature T, $\sigma_T = 1$°C

dewpoint temperature t, $\sigma_t = 1$°C ($\sigma_{RH} \approx 3\%$)

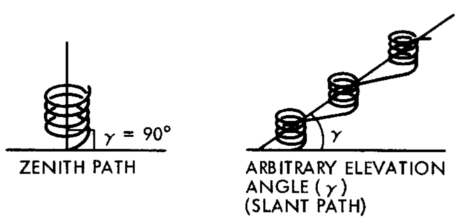
to the accuracies indicated.

The phase delay is computed

$$\Delta\rho = 6.11\,k \sum_i 10^{at_i/(t_i+b)} \frac{\Delta h_i}{(T+273)^2}$$

where a, b, k were defined in Eq. (1). Along the path the plane traveled, this system can yield approximately 95 percent calibration ($\sigma \lesssim 1$ cm).

Besides two-fold improvement in accuracy over radiosonde balloon zenith calibrations, the aircraft can fly a variety of topocentric elevation paths. This permits line-of-sight calibration for any arbitrary elevation angle.



Comparisons of aircraft and SMILE vapor calibrations (Fig. 2) show sub-centimeter agreement between the radiometer and aircraft phase delay computations.

The aircraft dewpoint temperature sensor apparently iced during the morning flight when the aircraft was above 3 km (10,000 ft). Assuming an exponential distribution for the water vapor above 3 km and noting that the aircraft system indicates the water vapor partial pressure to be near 0.1 mb at 3 km, the phase delay due to vapor above 3 km is computed to be < 0.14 cm. This small contribution plus the direct calibration derived from the MRI aircraft data below 3 km constitutes the "corrected aircraft" calibration point of Fig. 1.

Although this sample (two points) is not sufficient to permit a definite statement about the relative agreement of these two calibration schemes, it is encouraging. The SMILE regression coefficients, obtained by fitting to radiosonde data in May 1974, still seem valid. This apparent validity persists even though the regression coefficients were derived in May at El Monte by fitting to balloon data and are now being used in November at JPL and compared to aircraft instrument calibrations.

V. Radiometer-Radiosonde Comparisons: May 1975

In May 1975, at El Monte, California, a second comparison of radiometer–radiosonde calibrations was achieved (Fig. 3). The rms discrepancy between the 2 calibration sets is 1.1 cm. The regression coefficients for SMILE derived a year before at El Monte were used. The regression coefficients still appear valid.

It is of interest to note that on 29 of the 36 radiosonde balloon flights at El Monte, no data above ~ 2.7 km (9000 ft) were acquired. The remaining seven balloon flights produced data to altitudes of 6 km (20,000 ft). The adopted atmospheric water vapor scale height is about 2 km (Ref. 2). In theory, 36 percent of the water vapor medium exists at altitudes above the altitude of the scale height.

The radiosonde devices cannot measure relative humidity below the 20 percent level. Relative humidity is generally less than 20 percent for altitudes greater than 2.7 km. It is observed from balloon data that the relative humidity was about 20 percent at the 2-km altitude over El Monte during May 1975. For those radiosonde flights to 6 km altitudes where the relative humidity was measured at approximately a constant 20 percent, once the device was above 2 km altitude the electrical phase path delay was overestimated by ~ 10 percent.

Similarly, the phase path delay is underestimated by those balloon flights which terminate at less than 3 km if no effort is made to account for the higher altitude vapor, and no effort was made. The rms uncertainty of the radiosonde calibration with these noted deficiencies present is approximately 2 cm (1 σ). Thus the radiometer is shown to be at least as accurate as the radiosonde for this test period.

VI. Radiometer-Aircraft Comparisons: May 1975

In addition to the radiosondes, the aircraft used in November 1974 was also flown during this time. Meteorological data derived from aircraft instrumentation are superior to data obtained from radiosonde balloons. As indicated, the aircraft-based calibrations are 2- to 10-fold more accurate than the balloon-based calibrations. Additionally, the aircraft can sample the atmosphere every few seconds; the aircraft's path is under control, permitting "zenith-spiral ascents" or spiral ascents along varying topocentric elevation angles; and redundant instrumentation can be flown in the aircraft. All of these instrumentation advantages are exploited in this analysis.

There are some disadvantages. The ambient temperature probe has some "thermal inertia." Comparisons of ascent and descent thermal profiles (Fig. 4) show a systematic altitude bias between the ascent–descent thermal profiles. This altitude bias is present in all data. Analysis of all temperature profiles below 3 km indicates that the time delay of the aircraft temperature probe is 20 seconds (σ = 9 seconds). The temperatures reported by the instrument were experienced, on the average, 20 seconds earlier. This deficiency is of some consequence in the determination of the collective amount of water vapor along the aircraft's path. The temperature bias is 0.5 K. This translates to 0.2 cm, a 3 percent error, for the average weather conditions of May 1975 at El Monte.

Additionally, there are significant dewpoint temperature measurement errors as shown (Fig. 5). On May 5, for altitudes below 3 km, there appears to be a bias (0.7°C, 17 seconds in time, or 300 meters in altitude). Such a bias amounts to a 0.5-cm error in the phase path delay determination.

As shown in Fig. 4, there is a thermal inversion at approximately 4 km (13,000 ft) that amounts to a 10°C increase between 4 km (13,000 ft) and 4.8 km (16,000 ft). It it in this altitude zone that the "ascent" and descent" profile differs by 3 to 4°C. At these high altitudes, at very low ambient temperatures, the amount of water vapor is quite low, and thus such an inconsistency does not amount to more than 0.1-cm difference in the phase path determination. If such a dewpoint temperature measurement difference exists at low altitudes, at high ambient temperatures, as on May 16 (Fig. 5), the difference in the phase path determination is a few centimeters. Speculation as to which profile is correct, if either, can be obtained by comparing them to the relative humidity profile of the radiosonde of May 16 (Fig. 6). All of the ascent profiles (balloon, aircraft) appear similar, with some variance noted at the thermal inversion altitude. Thus the descent dewpoint profile is suspect.

The dewpoint temperature is measured by observing the temperature at which water vapor condensation occurs on a mirror as it is cooled down. If condensation should collect on the mirror and then freeze (and usually above 1.2 km (4000 ft) ambient temperatures are below the freezing point of water), the dewpoint is not determinable with such a device. This is thought to be the cause of such erroneous dewpoint measurements as do occur.

On the May 14 and 16 flights, two dewpoint devices were simultaneously measuring condensation temperatures at the aircraft. When thermal inversions were traversed on the ascent flights, and during the preponderance of the descent flights, the dewpoint measurements were significantly different (Fig. 7). This inconsistency indicates that some of the measurements are invalid.

On May 5 and 6, when atmospheric conditions were near the ideal (no thermal inversions, no atmospheric turbulence), the aircraft dewpoint temperature measurements were valid.

The rms discrepancy between zenith radiometer and "valid" aircraft calibrations (5 observations) is $<$ 1 cm (Fig. 8). There may be a small positive bias between aircraft and radiometer calibration that may relate to the fact that the May 1974 SMILE regression coefficients do not account for vapor above the radiosonde balloon flight altitudes ($>$ 3 km). However, the 5-point sample is too small to draw any definite conclusions on that point.

VII. Low Elevation Angle Observations

One of the principal advantages of the radiometer and the aircraft is that the accumulative amounts of water vapor (and thus the phase delay) can be measured not only at zenith as with the balloons but at a variety of different elevation angles.

Figure 9 compares aircraft and radiometer calibrations at an elevation angle of 10 deg. There are three aircraft calibration points denoted by the large circles with the arrows. Circle diameters indicate flight time; the arrows indicate an ascent or descent flight. The radiometer data points are shown as Rs.

During the 6 hours in which radiometer data were acquired on May 6 (Fig. 9) a "diurnal" fluctuation in the water vapor level is evident. From 10:00 (local time) to 14:00, the water-vapor-induced phase delay increased approximately 7 cm along the 10 deg elevation angle path through the atmosphere. The aircraft calibrations tell a consistent story. The indication is that the two systems are providing line-of-sight water vapor calibrations to the centimeter level or better. Figure 10 shows similar quantity comparisons for 20- and 30-deg elevation angle flight paths.

Thus, line-of-sight calibrations for varying elevation angles to better than the 2-cm level have been demonstrated by the radiometer for May 5 and 6, two days of nearly ideal weather, with no clouds, no thermal inversions, and no inhomogeneities apparent.

Less ideal weather was experienced on 14 May, which was the next occasion for the aircraft to acquire data. An overcast existed at the altitude of a rather large thermal inversion. There was a 6°C increase between the 600 m (2000 ft) and 1 km (3300 ft) altitudes. As stated earlier, the aircraft dewpoint temperature data (acquired simultaneously in time and space) did not agree. A similar situation was encountered on May 16, when the plane next operated.

Figure 11 shows aircraft instrument-radiometer calibration comparisons under ideal weather conditions (May 5, 1975) and under adverse weather conditions (May 16, 1975). As indicated, it is the aircraft-based calibration which is of suspect quality. However, the maximum difference, even under the adverse weather is 3 cm along the line of sight. This line-of-sight calibration at a 10-deg elevation angle is nearly an order of magnitude more accurate than the refraction model currently used to support deep space navigation of spacecraft.

VIII. Seasonal Refraction Model

The current refraction model (Ref. 4) is based on radiosonde balloon data acquired in 1967 and 1968. The two years of data were combined to yield monthly averages for the amount of water-vapor-induced phase path delay. Thus, a standard year for each DSS was defined. The rms discrepancy between the day-to-day fluctuations in the 1967–1968 data base and the monthly mean is approximately 4 cm. This is, of course, at zenith.

IX. Surface Weather Model

Once high-speed data lines become available, surface weather data from each DSS will be communicated to the Jet Propulsion Laboratory Control Center. Then DSS surface weather data

$$\text{absolute pressure } P, \sigma_P = 0.1 \text{ mb}$$

$$\text{ambient temperature } T, \sigma_T = 0.1°\text{C}$$

$$\text{dewpoint temperature } t, \sigma_t = 1.0°\text{C}$$

acquired to the accuracies indicated will yield water vapor calibrations for phase delay to an 85–90 percent accuracy (2.5 cm – 1 σ) in the zenith direction (Fig. 12). The model is based on the adiabatic law (Ref. 5).

X. Electrical Phase Path Delay for Observations at 10 deg Elevation Angle

At zenith, all calibration techniques discussed here—radiometer measurements, radiosonde measurements, aircraft measurements, seasonal model, and surface weather data model—yield one way range calibrations to better than 4 cm (σ). Inasmuch as the optical depth is 6 times greater at 10 deg than at 90 deg elevation, the zenith calibrations of the radiosonde, the seasonal refraction, and surface weather data models must be multiplied by nearly 6. And, correspondingly, the 1-σ uncertainties of each must be so multiplied by 6. At 10 deg, the radiosonde calibration has a 12-cm uncertainty (σ), while the seasonal model uncertainty is 24 cm and the surface model calibration uncertainty is 15 cm. The uncertainty of the radiometer, a line-of-sight calibration, is thought to be 1–2 cm at 10 deg elevation angle.

Figure 13 shows $\Delta\rho$ for 10-deg elevation angle observations under different weather conditions as derived from the radiosonde, surface weather, aircraft instrumentation, and radiometer. From the May 6 calibrations, subcentimeter agreement between aircraft and radiometer comparison is exhibited. Both calibrations show the same time history. Radiosonde and surface weather calibrations are centimeters apart from each other as well as from the aircraft and radiometer calibrations. The surface weather measurements indicate a general decrease in the water vapor level while the radiosonde measurements indicate a net increase. However, because of the uncertainties associated with these two "mapped" from zenith to line-of-sight calibrations, the radiosonde and surface weather model indicate temporal changes are not statistically significant.

As the weather conditions deteriorate, the discrepancy between the calibrations increases. This is due to the 6-fold magnification of the zenith errors in the surface data and radiosonde calibrations when those calibrations are "mapped" to 10 deg elevation angle.

XI. Conclusion

Line-of-sight radiometer calibrations for water vapor effects on range measurements are more accurate than radiosonde and/or surface weather model "mapped" calibrations. They are 5 to 10 times more accurate for range observations at 10 deg elevation angle when ideal weather exists. The performance of radiometers in adverse weather is yet to be determined.

Acknowledgments

The radiometer evaluated and discussed in this test was loaned to the Atmospheric Research Information Exchange Study (ARIES) Project (JPL) by the Microwave Radiometry Group (JPL), and was maintained and operated by The Space Radar and Microwave Radiometry Section (JPL). The aircraft flight activities were coordinated by Bill Giles of the Caltech Seismology Laboratory. The U.S. Weather Service kindly provided their radiosonde data; we are grateful for the cooperation from Ms. Patricia Burns and Mr. Larry Soussaman of the Weather Service's El Monte office. Dr. Joseph Waters (JPL) originally suggested this type of analysis and provided help and advice throughout the experiment.

References

1. Staelin, D. H., et al., "The Scanning Microwave Spectrometer (SCAMS) Experiment," *Nimbus 6 User's Guide*, Goddard Space Flight Center, 1975.

2. Waters, J., "Atmospheric Effects on Radio Wave Phase and the Correction of Vapor-Caused Phase Fluctuations by Radiometric Measurements of Water Vapor Emission," *VLA Scientific Memo* No. 8, NRAO, 1967.

3. Bean, B. R., and Dutton, E. J., *Radio Meteorology*, U.S. Dept. of Commerce, NBS, March 1, 1966.

4. Thuleen, K. L., and Ondrasik, V. J., *The Repetition of Seasonal Variations in the Tropospheric Zenith Range Effect*, TR 32-1526, Technical Report 32-1526, Vol. VI, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1971.

5. Chao, C. C., *New Method to Predict Wet Zenith Range Correction from Surface Weather Measurements*, Technical Report 32-1526, Vol. XIV, Jet Propulsion Laboratory, Pasadena, Calif., Apr. 15, 1973.

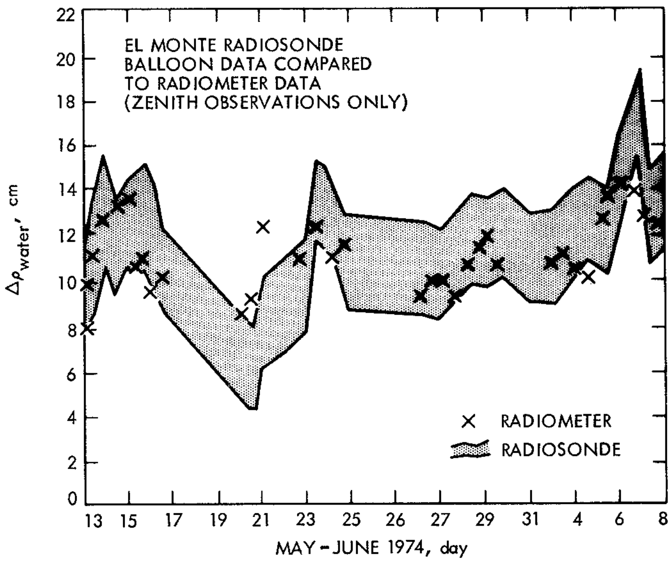


Fig. 1. Comparisons of radiometer/radiosonde/aircraft calibrations, May-June 1974

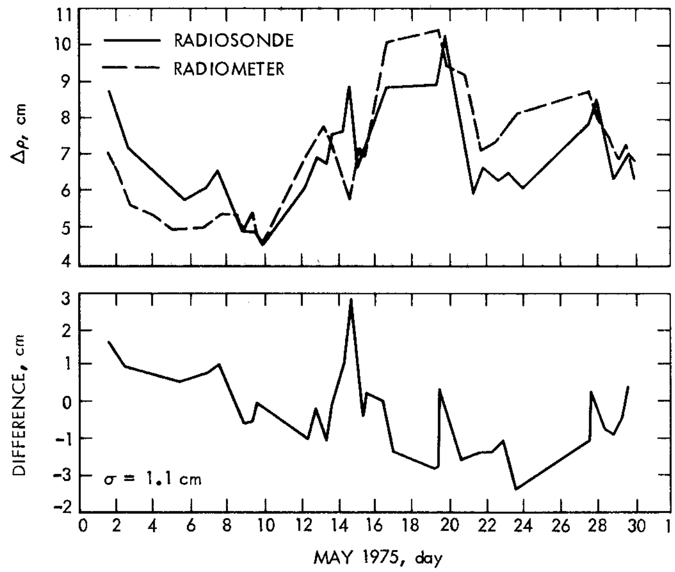


Fig. 3. Comparisons of zenith radiosonde/radiometer calibrations (31 observations), May 1975

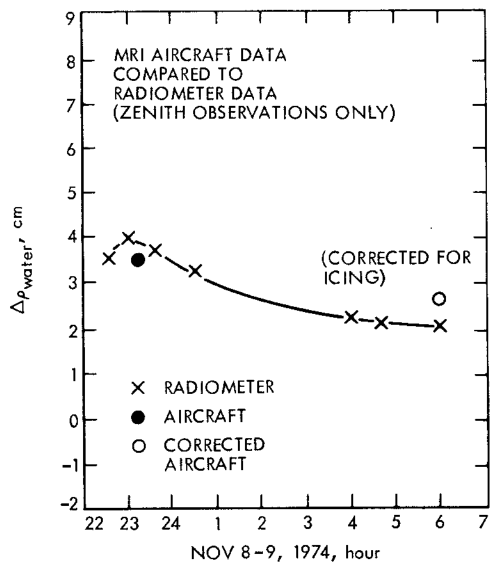


Fig. 2. Comparisons of radiometer/aircraft water vapor calibrations, Nov. 8, 1974

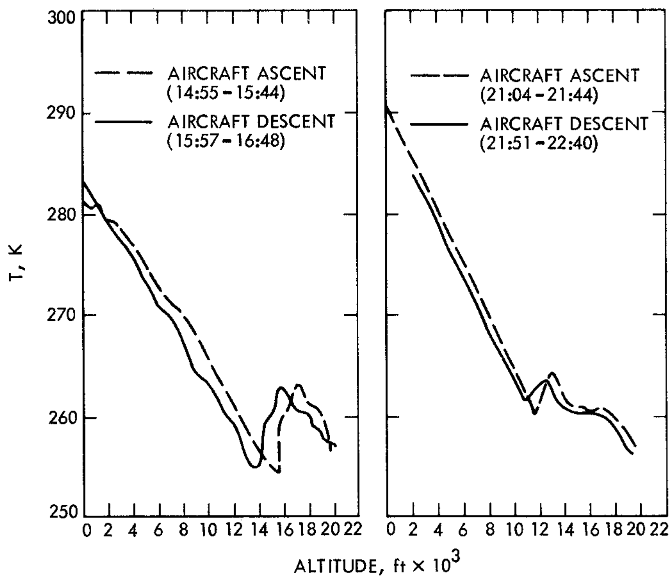


Fig. 4. Evidence of temperature/altitude profile biases, May 5, 1975, El Monte, Calif.

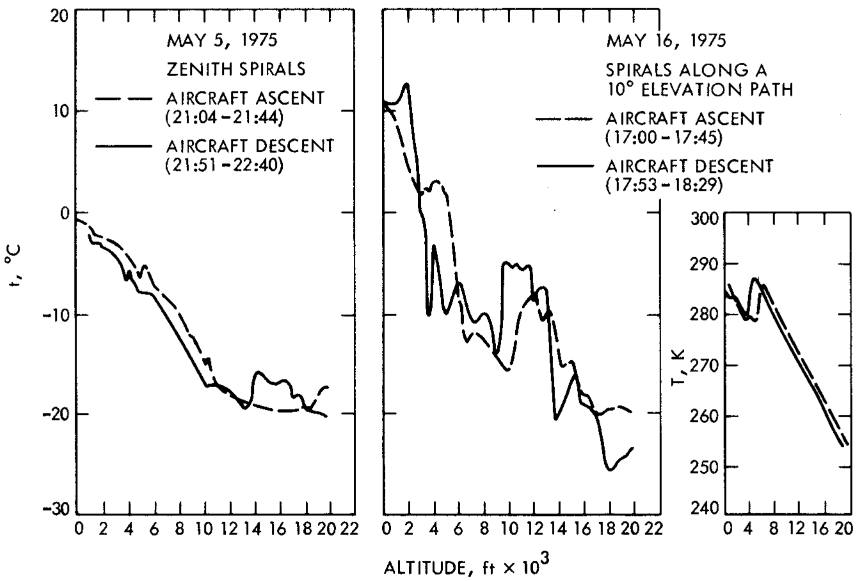


Fig. 5. Evidence of dewpoint temperature measurement error, El Monte, Calif.

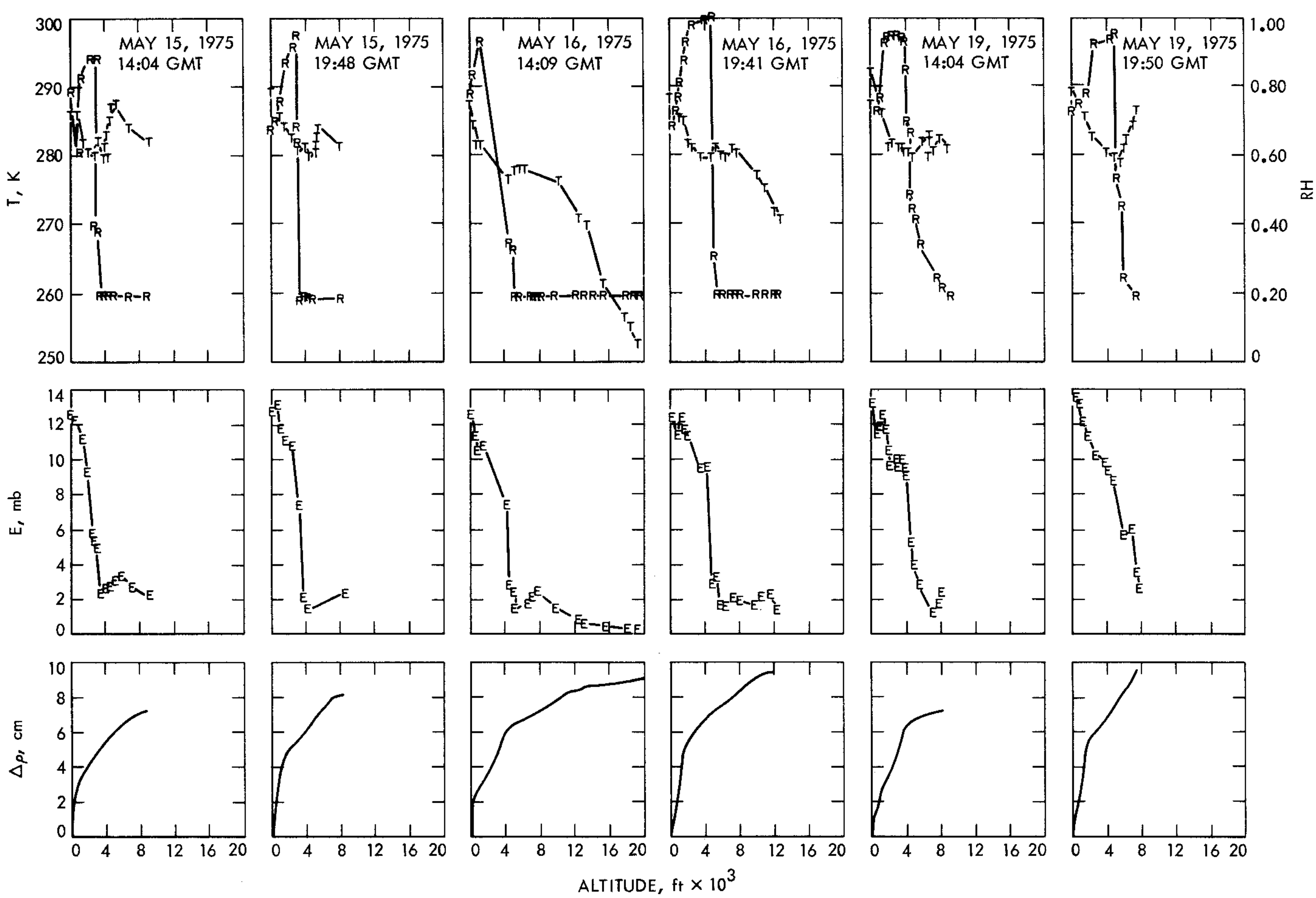


Fig. 6. Radiosonde variables: vertical gradients, El Monte, Calif. (T = temperature, R = relative humidity, E = refractivity due to water vapor)

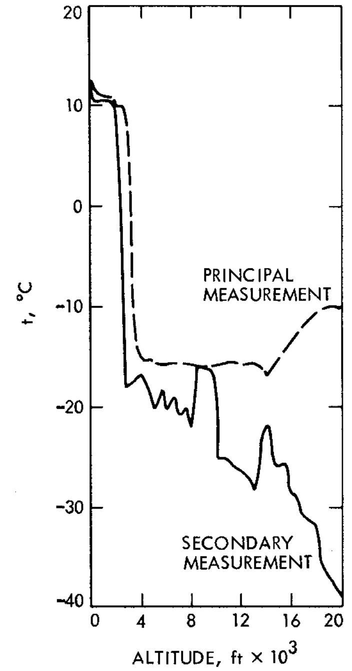


Fig. 7. Inconsistencies of dewpoint temperature/altitude profile

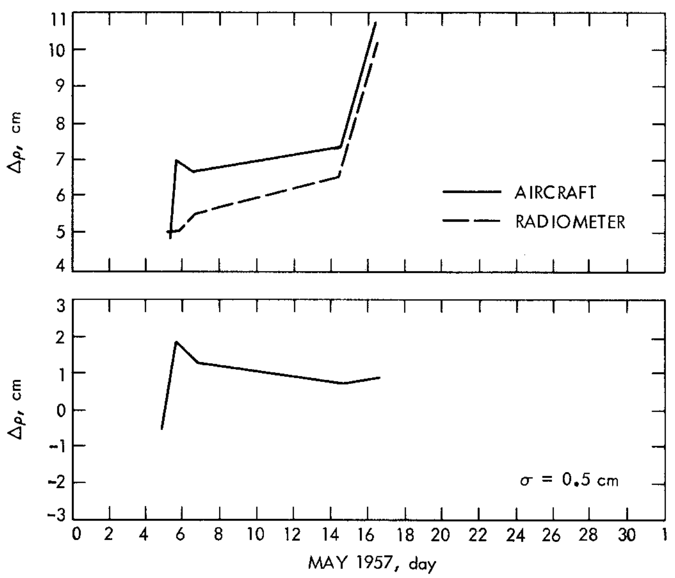


Fig. 8. Comparisons of zenith aircraft/radiometer calibrations (5 observations), May 1975

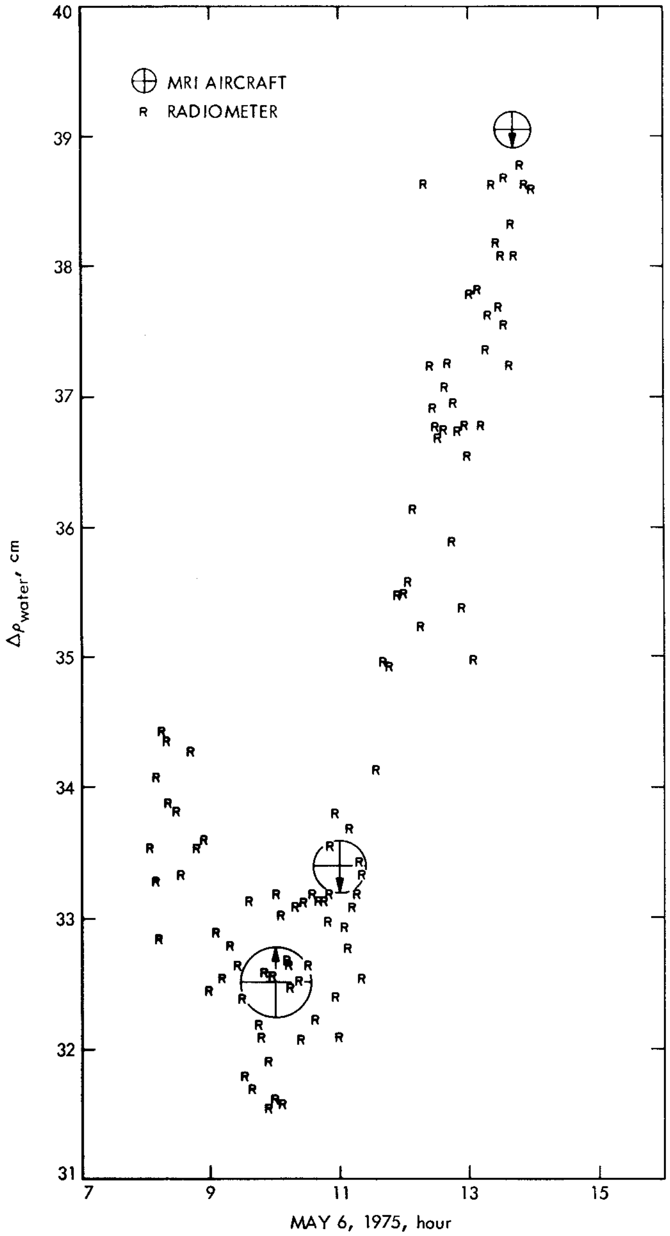


Fig. 9. Comparisons of radiometer/aircraft water vapor phase delay calibrations, line of sight (10° topocentric elevation)

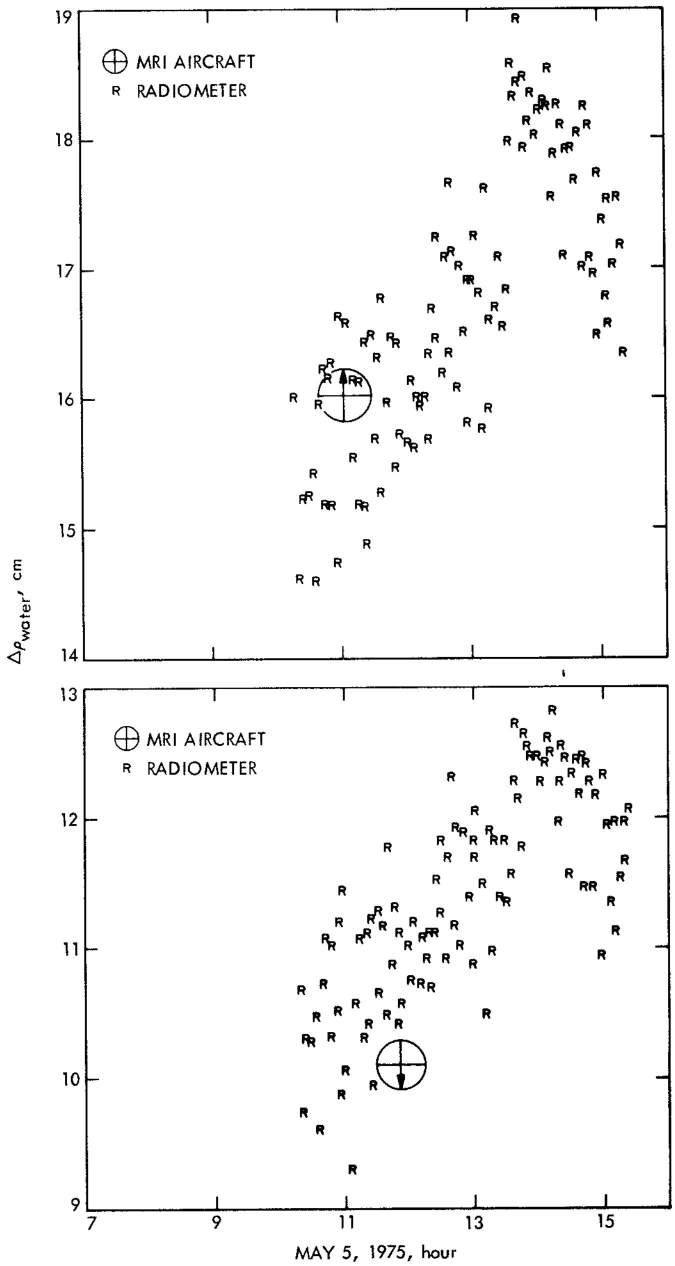


Fig. 10. Comparisons of radiometer/aircraft water vapor phase delay calibrations, line of sight (20 and 30° topocentric elevation angles)

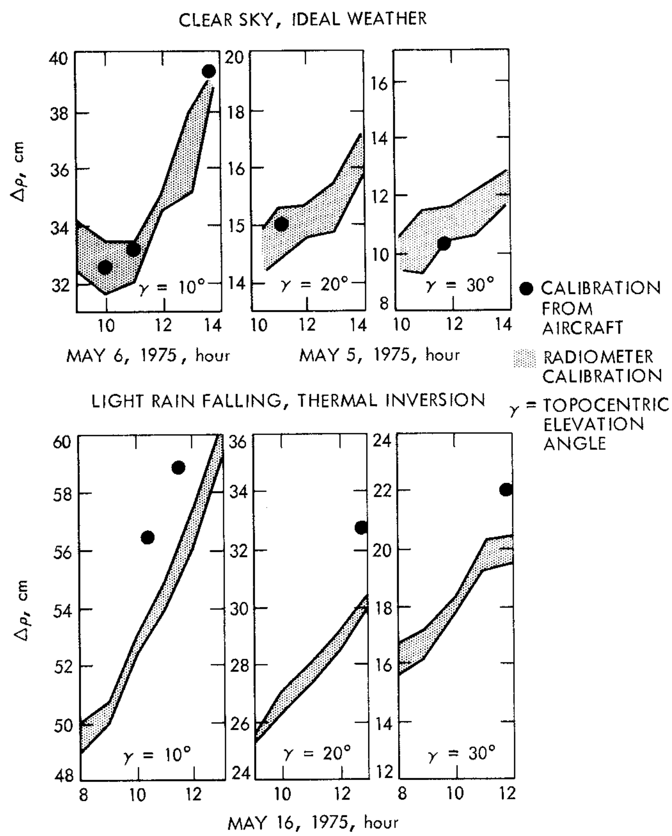


Fig. 11. Comparisons of aircraft instrument and SMILE radiometer calibrations

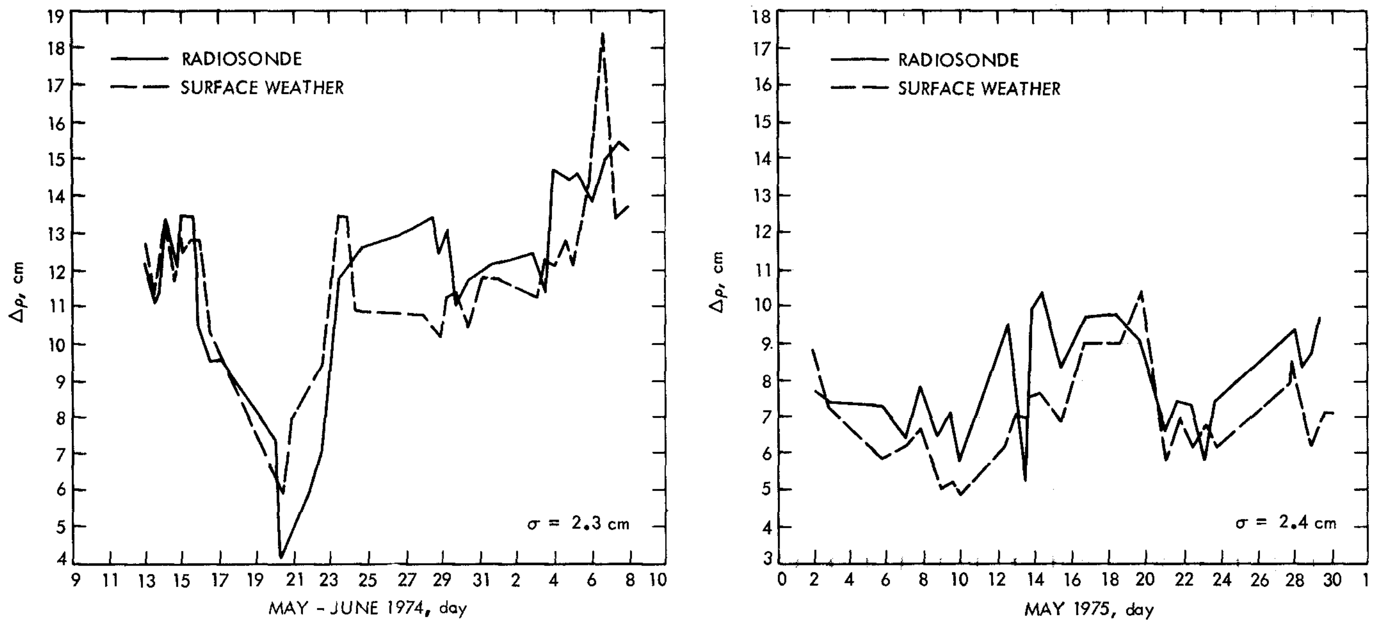


Fig. 12. Comparisons of surface weather data and radiosonde data calibrations, El Monte, Calif.

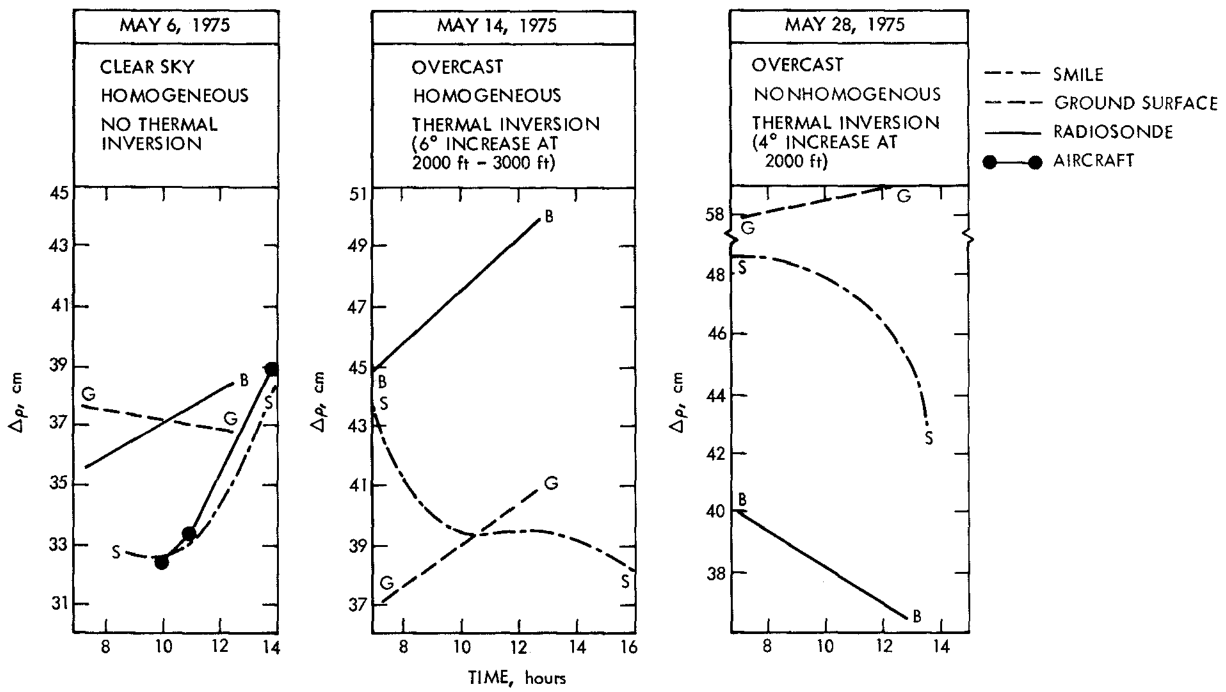


Fig. 13. S-band electrical phase path delay for observation at 10° elevation angle, El Monte, Calif.